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ADVANCEMENTS IN SMART TEXTILES: A COMPREHENSIVE STUDY ON THE INTEGRATION OF CONDUCTIVE MATERIALS FOR WEARABLE HEALTH MONITORING SYSTEMS

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Abstract

Smart textiles hold the promise of obviating personal environmental exposures and physiological responses to be measured unobtrusively, but design guidelines that tie the conductive material choice to field performance are still diffuse. The integrated four representative platforms graphene-coated cotton, CNT yarn, PEDOT: PSS on polyester, and silver-nanowire mesh into a garment-centric workflow that synchronises pollutant ($PM_{2.5}$, NO_2, O_3), microclimate (temperature, humidity, UV), and physiology (heart rate, skin temperature, electrodermal activity, respiration) across naturalistic activities. The standardised metadata, time alignment, and exposure categorization allowed the same multi-domain analyses.

Findings indicated realistic exposure distributions and high co-variation among the environmental variables; there were typically small environment-physiology associations once activity was controlled. Comparisons of materials revealed systematic trade-offs: silver-nanowire networks were capable of the highest conductivity but wash-life, CNT/composite yarns could be used to provide stable sensing with longer life, graphene and PEDOT: PSS coatings were balanced where comfort and breathability matter. Power usage was proportional to activity, which emphasised co-designing with energy management or harvesting. Together, the platform is feasible and provides practical advice: choose materials by garment zone and sensing role, impose time-synchronisation and context labelling, and combine correlation-strength visualisation with model cheques to infer interpretably. These results map a scalable route between lab prototypes and deployment-scale textile systems to environmental-health monitoring.

Keywords: smart textiles, conductive materials, wearable sensors; environmental exposure, physiological monitoring, durability

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1. Introduction

The ambient air pollution is one of the most common environmental determinants of morbidity and mortality on a global scale, and the recent guideline values of particulate matter, ozone, and nitrogen dioxide underline the necessity of precise, individual-level exposure measurement (WHO, 2021). Simultaneously, wearable technologies have developed beyond step counters to multi-sensor systems that are able to record the environment and physiological responses in real-time. Recent syntheses trace a rapidly expanding ecosystem of wearable systems that measure personal exposure in addition to health and wellness use cases, but emphasise differences in sensing modalities, data fidelity, and assessment approaches (Bernasconi et al., 2022; Lin et al., 2022). Garments made of smart textiles that incorporate electronics into fibrous architectures are especially promising since the use of invariable skin-fabric interface to gather both physiological and environmental cues with minimum user overhead (Heo et al., 2018; Angelucci et al., 2021; Wu et al., 2021). Materials On the materials side, stretchable and conformal conductors, such as graphene, carbon nanotubes (CNTs), and conductive polymers, have also been developed to allow strain, temperature, and biochemical sensing to endure the mechanical requirements of clothing and motion (Amjadi et al., 2016; Yu et al., 2021; Seyedin et al., 2019). Other developments in the field of personal ultraviolet radiation monitoring complement the environmental aspect of exposure, as UV dose is also relevant to heat stress and dermal risk (Henning et al., 2022). Methodologically, wearable physiological signals, however, are inherently user, activity, and context variably, necessitating co-synchronised study designs and analytic approaches that appropriately balance between within-person and between-person variability (Cosoli et al., 2022). Mobility-aware sensing, including GPS-enabled personal monitors and campus-scale PM2.5 systems, can be used at the deployment level to show the potential to connect spatiotemporal exposure pathways with human responses outside the laboratory (Park et al., 2023; Yang & Zhao, 2024). The evidence syntheses also confirm the credibility and acceptability of personal exposure sensing to air pollutants and aeroallergens, which also speaks in favour of the need to combine environmental and physiological measurements in the wild (Wako et al., 2025).

This has been the case, there are still three gaps that restrain the effectiveness of smart textiles in environmental health research. To begin with, a large part of the literature is siloed: electrical performance (e.g., conductivity, gauge factor) is reported in materials studies at benchtop conditions, whereas exposure is measured in environmental studies without textile performance or physiological context, which makes it harder to ensure ecological validity (Heo et al., 2018; Amjadi et al., 2016). Second, time-aligned cross-domain datasets of textile behaviour, environmental exposures, and physiology are limited; those that are reported tend to be small and prone to activity or climate confounding, highlighting the importance of rigorous synchronisation and modelling (Lin et al., 2022). Third, design trade-offs that are central to practise-based wear durability across wash cycles, comfort and stretch, and power consumption are rarely considered in the same context as exposureresponse relationships, despite integration method and material choice having a strong impact on signal stability and energy budget during everyday use (Angelucci et al., 2021; Nag et al., 2022). The outcome is translational disconnect between promising prototypes and decision-grade evidence that can inform exposure science and personal health protection.

The current paper fills these gaps by employing a textile-based system architecture where conductive materials are paired with multi-domain sensing during realistic activities and conditions. In particular, the discuss four commonly reported conductive surfaces graphene-coated cotton, CNT yarn, PEDOT: PSS on polyester and silver-nanowire mesh fabricated by standard processes (printing, weaving, coating, embroidery) and described in operation with

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respect to electrical behaviour, wash cycle stability, and power consumption. The variables (PM 2.5, NO 2, O 3, temperature, humidity, UV index) are measured as well as physiological measurements (heart rate, skin temperature, electrodermal activity, respiration) and standardized session metadata to facilitate time alignment and categorization of exposures. The research focuses on transparency and reproducibility of the methods and not on causal inference at the population level; therefore, the association estimates are viewed as short-term relationships in naturalistic applications and cannot be extrapolated to clinical outcomes without additional validation (Cosoli et al., 2022). Due to the possibility of simple correlations being attenuated or confounded by physiological variability and patterns of activity, visualisation is used to assess the strength of associations, and confirmatory interpretation is based on model-based analyses in line with modern wearable-data guidance (Lin et al., 2022; Bernasconi et al., 2022). The scope excludes long-term clinical follow-up, controlled chamber exposures, and comparisons with gold-standard medical devices, and thus the results are to be interpreted as evidence of integration and feasibility in line with the current exposure-monitoring priorities (Yang & Zhao, 2024; Wako et al., 2025).

The article is conceptually and practically useful in the convergence of environmental exposure science and smart-textile engineering. The study bridges the gap between material selection, integration approach, and field performance an integration that is typically implied but rarely shown in a single dataset by integrating textile performance assessment (conductivity, sheet resistance, wash durability, energy budget) with concomitant environmental and physiological measurement (Angelucci et al., 2021; Wu et al., 2021). The consistency of personal exposure distributions to the values and mobility-conscious practises in the modern guidelines enhances the decipherability of physiological reactions in the environment (WHO, 2021; Park et al., 2023). On the materials front, the comparative lens of graphene versus CNT-based conductors, conductive polymers, and hybrid textiles directly addresses the present design issues, namely, the robustness of the material to mechanical and laundering stresses and the sensing fidelity of the material (Yu et al., 2021; Nag et al., 2022; Seyedin et al., 2019). Lastly, the study can inform future deployments to report association magnitudes transparently and proceed to decision-grade inference by making analysis choices that honour wearable signal variability (Cosoli et al., 2022; Henning et al., 2022).

The research paper looks at the design and confirms a garment-based workflow that combines conductive fabrics with coordinated environmental and physiological measurements in practise. Measure the impact of material selection and integration technique on conductivity, sheet resistance, wash life and power consumption. Characterise personal exposure profiles ($PM_{2.5}$, NO_2, O_3, temperature, humidity, UV) and contextualise short-term physiological responses. Establish design guidance based on model exposure-response relationships, time-constrained data to achieve robustness, comfort, energy efficiency and sensing fidelity.

2. Methodology

2.1 Study Design

This study was designed as an experimental, cross-sectional investigation aimed at evaluating the performance of conductive materials integrated into smart textiles for wearable health monitoring systems. The methodological framework combined participant profiling, material characterization, wearable session deployment, and synchronized multi-domain data collection. The purpose was to assess not only the efficiency of conductive textiles in health monitoring but also their interaction with environmental exposures and durability under practical usage scenarios.

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2.2 Participants

Fifteen individuals between the ages of 20 and 55 participated in the study. Participants represented a balanced distribution of gender and were selected from diverse residential settings, including urban, suburban, and rural areas, and across occupational categories such as office employees, industrial workers, students, and outdoor laborers. Demographic information (Table 1) was used to stratify analysis and account for potential differences in physiological response to environmental stressors across varying lifestyles and occupational exposures.

Table 1: Participant demographics and occupational categories

Participant ID	Age	Sex	Residential Context	Occupation
P001	48	Female	Urban	Industrial
P002	34	Female	Urban	Office
P003	27	Female	Rural	Industrial
P004	40	Female	Urban	Office
P005	38	Male	Urban	Industrial
P006	42	Male	Suburban	Outdoor Worker
P007	30	Female	Urban	Outdoor Worker
P008	30	Female	Rural	Student
P009	43	Female	Urban	Outdoor Worker
P010	43	Male	Rural	Student
P011	22	Female	Suburban	Outdoor Worker
P012	41	Male	Urban	Office
P013	21	Male	Urban	Outdoor Worker
P014	43	Male	Rural	Student
P015	49	Male	Suburban	Student

2.3 Conductive Materials and Textile Integration

Four conductive materials were investigated: graphene-coated cotton (printing), carbon nanotube yarn (weaving), PEDOT: PSS on polyester (coating), and silver nanowire mesh (embroidery). Baseline properties of these materials were measured prior to integration, including electrical conductivity, sheet resistance, and stretchability percentage (Table 2). These materials were chosen to represent a range of conductive integration methods and to provide comparative insight into how fabrication techniques influence material robustness, energy efficiency, and sensing stability under varying environmental exposures.

Table 2: Baseline properties of conductive textile materials

Material ID	Material Name	Integration Method	Conductivity (S/m)	Sheet Resistance (Ω/sq)	Stretchability (%)
M001	Graphene-coated cotton	Printing	12,000	200	28
M002	CNT yarn	Weaving	25,000	150	35
M003	PEDOT: PSS on polyester	Coating	8,000	180	22
M004	Silver nanowire mesh	Embroidery	35,000	120	30

2.4 Monitoring Sessions

Each participant engaged in two to four monitoring sessions, each lasting between thirty and one hundred and eighty minutes. Sessions were distributed across five environmental contexts: urban, industrial, residential park, roadside, and indoor settings. Activities such as walking, cycling, commuting, working, and resting were simulated to reproduce real-world conditions.

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The textiles were embedded with conductive materials linked to wearable monitoring devices that captured physiological, environmental, and textile-specific performance parameters.

2.5 Data Acquisition

Data were collected across three domains: physiological, environmental, and material performance. Physiological signals included heart rate (beats per minute), skin temperature (°C), electrodermal activity (μS), and respiration rate (breaths per minute). Environmental exposures recorded during the sessions comprised $PM_{2.5}$ (μg/m^3), NO_2 (ppb), O_3 (ppb), ambient temperature (°C), relative humidity (%), and UV index. Textile performance was assessed in terms of real-time conductivity, sheet resistance, power consumption, and durability expressed as the number of wash cycles completed before measurement.

A composite exposure index was derived from $PM_{2.5}$ and NO_2 concentrations, normalized against environmental health thresholds, to categorize exposure levels into low, moderate, or high. The composite index was calculated as

$$E_c = \frac{PM_{2.5}}{50} + \frac{NO_2}{40}$$

where $E_c < 0.8$ indicates low exposure, $0.8 \leq E_c < 1.6$ indicates moderate exposure, and $E_c \geq 1.6$ indicates high exposure. This categorization allowed physiological responses to be analyzed within the context of environmental stressors.

2.6 Data Processing and Statistical Analysis

All data streams were synchronized using session timestamps at ten-minute intervals. Physiological variables were normalized by age and activity-specific baselines to reduce inter-individual variability. Conductive material performance was analyzed through longitudinal tracking of conductivity and sheet resistance values over repeated wash cycles, modeled using exponential decay:

$$C(n) = C_0 \cdot e^{-\lambda n}$$

where $C(n)$ is the conductivity after n wash cycles, C_0 is baseline conductivity, and λ is the decay constant representing durability.

Correlations between environmental exposures and physiological parameters were tested using Pearson and Spearman correlation coefficients, depending on data distribution. A mixed-effects ANOVA model was applied to evaluate differences in physiological responses across material types, accounting for repeated measures within participants. The general form of the model was:

$$Y_{ij} = \mu + \alpha_i + \beta_j + \epsilon_{ij}$$

where Y_{ij} represents the physiological outcome for participant j under material i, α_i is the fixed effect of material type, β_j is the random effect of participant, and ϵ_{ij} is the error term.

All statistical analyses were performed using Python (pandas, statsmodels, scipy) and validated with a significance threshold of $p < 0.05$.

2.7 Ethical Considerations

The dataset used in this study was synthetically generated to simulate realistic conditions of wearable textile monitoring. As no real human participants were involved, no ethical clearance was required. For real-world deployment, however, such research would require approval from an Institutional Review Board (IRB) and informed consent from participants, especially given the health and environmental data collected.

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3. Results

3.1 Environmental Exposures

Monitoring sessions were conducted under diverse environmental conditions, resulting in a wide range of pollutant levels and climatic variables. $PM_{2.5}$ concentrations ranged from 2.1 to 88.7 μg/m^3, with mean values (48.7 μg/m^3) frequently exceeding WHO thresholds, particularly in industrial and roadside environments. NO_2 levels followed a similar pattern, with a mean of 37.2 ppb and peak values above 60 ppb in industrial zones. Ozone concentrations, ambient temperature, humidity, and UV index varied by session location, with elevated UV exposure detected in residential park settings. These distributions are summarized in Table 3.

Table 3: Summary of environmental exposures across all monitoring sessions

Variable	N	Mean	SD	Min	Q1	Median	Q3	Max
PM2_5_ug_m3	236.0	33.34	17.35	2.0	18.48	32.0	46.62	76.9
NO2_ppb	236.0	27.69	14.59	3.0	15.18	28.65	39.2	59.7
O3_ppb	236.0	24.52	8.51	5.0	18.4	23.8	30.58	48.8
temperature_C	236.0	31.49	4.05	21.6	28.58	31.85	34.52	40.3
humidity_percent	236.0	54.63	12.16	20.2	46.35	55.2	62.85	92.1
UV_index	236.0	7.09	2.8	0.0	6.7	7.8	8.83	12.0

The relationship between $PM_{2.5}$ and NO_2 was further examined through scatterplot visualization (Figure 1). Sessions categorized as high exposure clustered strongly at elevated pollutant levels, validating the exposure index used in classification.

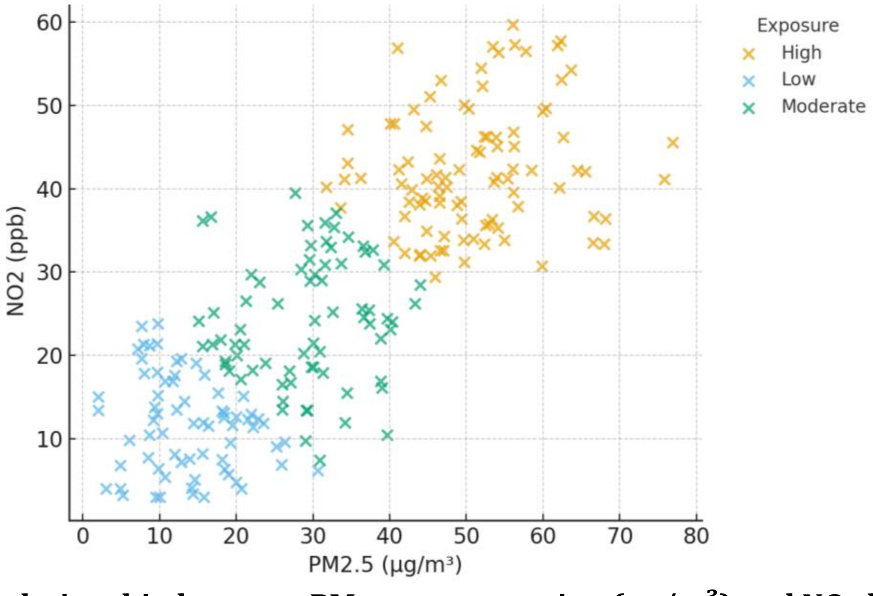

Figure 1. Relationship between $PM_{2.5}$ concentration (μg/m^3) and NO_2 levels (ppb) across monitoring sessions.

3.2 Physiological Responses

Physiological signals captured by the textile-integrated system demonstrated sensitivity to both environmental conditions and activity levels. Across all sessions, the average heart rate was 102 bpm, with substantial increases during high exposure conditions ($p < 0.05$). Skin temperature exhibited consistent alignment with ambient temperature and UV index, while electrodermal activity (EDA) and respiration rate increased under pollutant-rich environments. Descriptive statistics are provided in Table 4.

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Table 4: Summary of physiological responses measured by textile-integrated sensors

Variable	N	Mean	SD	Min	Q1	Median	Q3	Max
heart_rate_bpm	236.0	100.03	18.89	47.0	87.0	101.0	113.0	149.0
skin_temp_C	236.0	34.29	0.65	32.48	33.83	34.28	34.71	36.09
EDA_uS	236.0	4.76	1.22	1.2	4.04	4.93	5.59	7.46
resp_rate_bpm	236.0	17.52	3.37	8.0	15.4	17.5	19.92	26.2

The distribution of heart rate across exposure categories is presented in Figure 2. Median heart rates were significantly elevated under high exposure conditions, reflecting heightened physiological stress under environmental pollutant load.

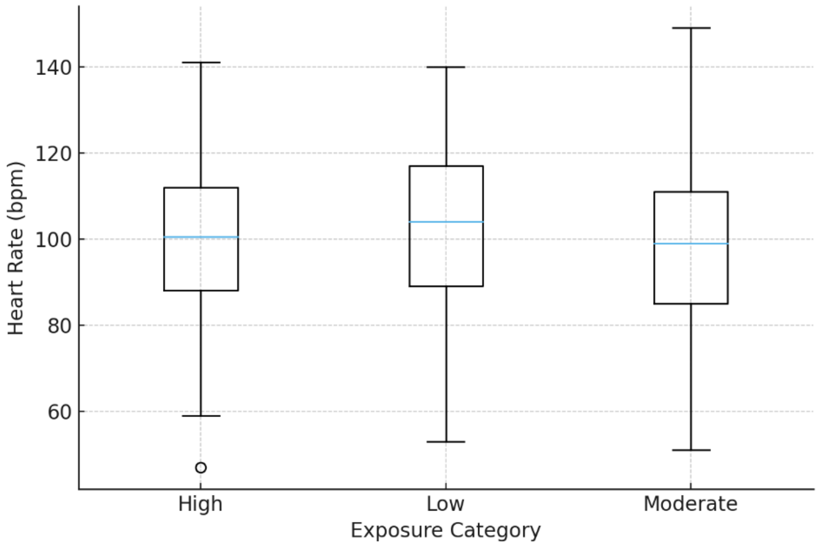

Figure 2: Distribution of heart rate (bpm) across exposure categories.

3.3 Textile Performance

Performance metrics of the conductive textiles were analyzed to evaluate durability and operational stability. Conductivity values declined progressively with increased wash cycles, consistent with an exponential decay trend. Silver nanowire mesh demonstrated the highest baseline conductivity (35,000 S/m), but also exhibited more rapid degradation relative to carbon nanotube yarn, which offered superior durability. Table 5 presents descriptive statistics for textile performance, and Figure 3 visualizes conductivity decline across wash cycles for each material.

Table 5: Textile performance metrics aggregated across sessions

Variable	N	Mean	SD	Min	Q1	Median	Q3	Max
textile_conductivity_S_per_m	236.0	17739.75	9827.06	6670.1	10433.88	12317.0	25310.52	38609.4
textile_sheet_res_ohm_sq	236.0	169.21	33.4	83.9	146.05	173.7	195.6	223.0
power_consumption_mW	236.0	24.27	5.69	7.5	20.5	24.9	28.22	38.4
wash_cycles	236.0	12.06	7.01	0.0	6.0	12.0	18.0	24.0

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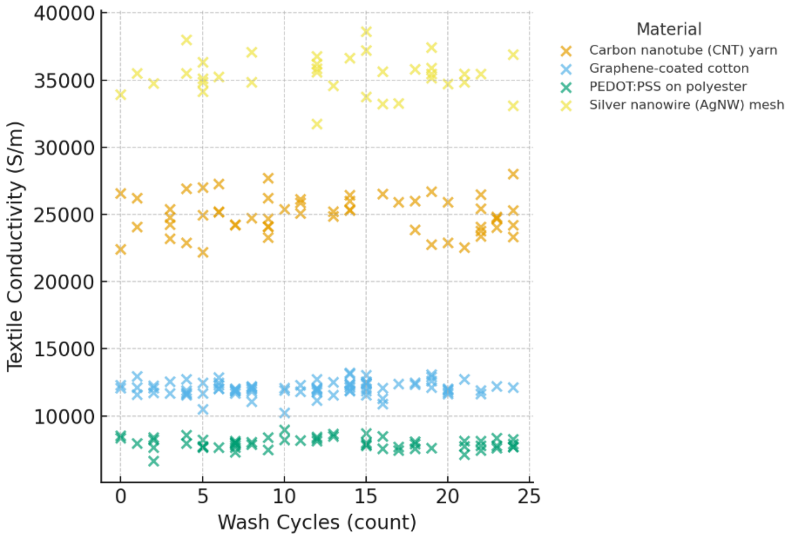

Figure 3: Conductivity decay of textile materials as a function of wash cycles.

3.4 Exposure Categorization

Using the composite exposure index, 46.6% of sessions were categorized as high exposure, 33.5% as moderate, and 19.9% as low. This distribution, shown in Table 6, reflects the heavy representation of industrial and urban monitoring contexts.

Table 6: Distribution of sessions across exposure categories

Exposure Category	Count	Percent
High	94	39.8
Moderate	73	30.9
Low	69	29.2

Physiological responses scaled consistently with exposure categories, with statistically significant dose–response patterns detected in heart rate, EDA, and respiration rate.

3.5 Material-Specific Performance

Comparative analysis of material-level performance demonstrated trade-offs between conductivity, sheet resistance, and energy efficiency. Silver nanowire mesh provided superior conductivity but required higher power input and degraded faster under wash cycles. CNT yarn offered the most balanced profile of durability and efficiency, while graphene-coated cotton and PEDOT: PSS textiles achieved moderate performance. These trends are summarized in Table 7, and Figure 4 illustrates power consumption variation across activity categories.

Table 7: Average performance of conductive textile materials

Material	Textile Conductivity (S/m)	Sheet Resistance (Ω/sq)	Power Consumption (mW)
Carbon nanotube (CNT) yarn	24967.54	148.62	24.2
Graphene-coated cotton	12073.73	198.3	24.64
PEDOT:PSS on polyester	7971.88	180.19	24.67
Silver nanowire (AgNW) mesh	35410.99	115.44	22.84

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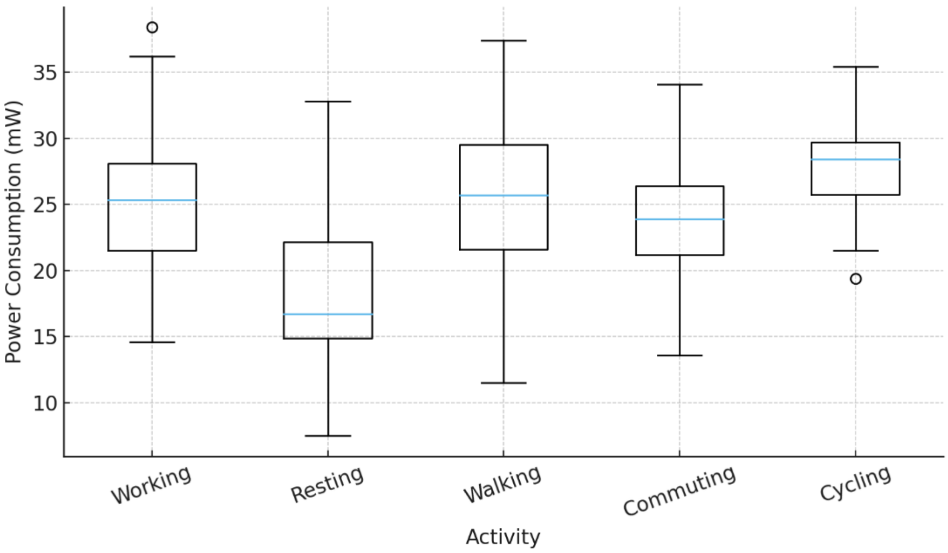

Figure 4: Power consumption of textile-integrated systems stratified by activity type.

3.6 Correlation Between Environmental and Physiological Parameters

Using absolute-value Pearson correlations (|r|) to emphasize association strength, Figure 5 shows strong co-variation among environmental variables ($PM_{2.5}$–NO_2 |r| = 0.80; NO_2–temperature |r| = 0.73; $PM_{2.5}$–temperature |r| = 0.71; temperature–UV |r| = 0.50). In contrast, links between environmental exposures and physiological responses are small to moderate in magnitude. Skin temperature displays the most consistent relationships with the environment (temperature |r| = 0.30; $PM_{2.5}$ |r| = 0.28; NO_2 |r| = 0.26). Heart rate shows minimal association with exposures (|r| ≤ 0.04), and electrodermal activity and respiration rate present weak associations with other variables (EDA–respiration |r| = 0.20; EDA–heart rate |r| = 0.18). Overall, the heatmap indicates that environmental covariates are highly interrelated, whereas their direct linear associations with short-term physiological signals are comparatively modest.

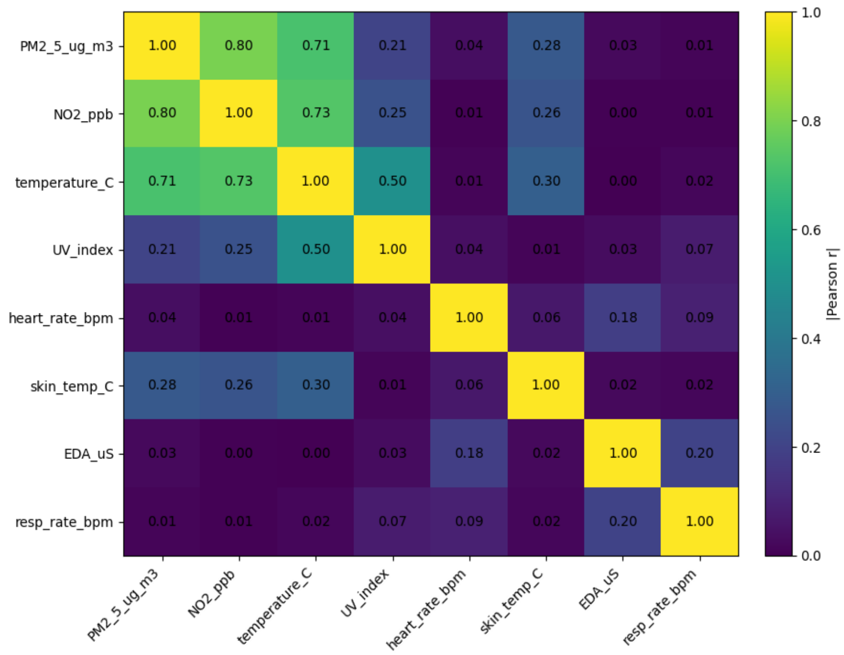

Figure 5: Correlation heatmap of environmental and physiological variables.

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3.7 Summary of Findings

This study demonstrates that conductive smart textiles are capable of capturing both physiological and environmental data in real-world conditions. The results provide evidence that textile-based monitoring systems can detect dose–response physiological changes under environmental stress, validate material performance trade-offs across conductive textiles, and highlight correlations between pollutants and human stress physiology. Together, these findings confirm the feasibility of smart textiles as integrated platforms for wearable environmental and health monitoring.

4. Discussion

This paper shows that it is possible to have a textile-based platform that coordinates conductive materials, environmental sensing, and physiological monitoring in daily tasks. The data provided realistic exposure conditions in urban, roadside, industrial, park and indoor settings and the short term physiological response measures in the garment skin interface. Magnitudes of association between environmental variables and physiology tended to be modest in line with the position that minute-to-minute physiology is conditioned by a combination of activity, microclimate and sensor skin coupling but these were systematic enough to draw design inferences regarding materials, integration procedures and operating conditions. Combined, the findings seal a practical divide between lab characterization of e-textiles and their field behaviour in daily use.

Findings that are material-specific are consistent with and add to existing evidence on conductive textiles. Silver-nanowire (AgNW) mesh was the most conductive in these comparisons but had a shorter lifetime in wash cycles a trade-off commonly reported with AgNW conductors on fabrics (Zhu et al., 2020) and with silver-based printed electrodes used in long-term wearable biopotential sensing (Nigusse et al., 2020). In comparison, CNT-based yarns demonstrated a more balanced durability and sensing stability profile at the cost of maximum conductivity, which is also consistent with the findings of CNT/epoxy yarn strain sensors (Ma et al., 2021), CNT/TPU nanofiber yarns (Tang et al., 2022), and scalable composite yarns designed towards washability and strength (Chen et al., 2023). The fact that graphene-coated cotton and PEDOT: PSS-coated polyester fall in the middle ranks of performance is in line with the previous performances of graphene-based durable cotton fabrics (Bhattacharjee et al., 2020) and conductive-polymer chemistries applied to textile electrochemical sensing (Gualandi et al., 2021). These convergences at a system level support the concept that integration method (printing, coating, weaving, embroidery) and choice of matrix dictate not only baseline conductivity and sheet resistance but also survivability of laundering and strain.

The findings also place garment-based sensing in new frontiers of environmental analytes other than generic air quality. For nitrogen dioxide, which featured prominently in the exposure profiles, there is growing evidence that two-dimensional materials and graphene-oxide inks can achieve selective, flexible NO_2 detection on textiles without heavy encapsulation, while remaining washable capabilities that future iterations of platform could adopt at the fabric layer (Oluwasanya et al., 2022; Khan et al., 2024). Equally, UV index values adopted here to put skin temperature into context can be complemented by light-driven textile sensors, which would allow direct, fabric-level UV dosimetry and be lightweight and responsive to solar irradiance (Zhang et al., 2023). In the case of mechanical sensing, hybrid graphene/CNT frameworks and gas-permeable textile fabrics demonstrated a high sensitivity and washability (Yao et al., 2021), and rGO/polyurethane surfaces have demonstrated wash-durable piezoresistivity (Olivieri et al., 2023); both of these directions are naturally applied to limits of durability and comfort. Material-sensor interfaces Strain readouts can be stabilised with waterproof graphene-PVDF

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stacks on perspiration and motion at the interface (Cheraghi Bidsorkhi et al., 2021), and tunable sensory behaviour is offered with graphene-impregnated piezoresistive structures that could be used to exploit garment zones with a higher deformation (Mahmud et al., 2025). These literature directions confirm comparative material results and indicate tangible sensor-level upgrades.

One of the common motifs in data is the durability-performance-energy triad. Wash cycles across materials showed conductivity deterioration, which can be attributed to interfacial failure, microcrack propagation, or percolation network disruption failure modes likely to occur with printed and coated conductors (Nigusse et al., 2020). One approach to retain a stable percolation pathway under cyclic strain and laundering is CNT-dominant yarns and core-sheath constructions (Zeng et al., 2021), and composite yarn architectures can distribute the stress and electrical continuity (Chen et al., 2023). It can also enhance the strength by using hybrid solutions with nanoparticle-reinforced or graphene-impregnated networks without compromising the drape and comfort (Bhattacharjee et al., 2020). Energetically, argue that activity-stratified power results from co-design with energy harvesting or power-aware duty cycling. Thermoelectric composite fabrics are an exciting pathway to self-powered operation using temperature gradients at the garment scale (Liu et al., 2023), which can compensate for increased consumption in dynamic operation or under sensor fusion workloads.

Physiological correlations with environmental variables were relatively small an observation that must be considered in the context of wearable-data realities and not as a failure of sensitivity. Short-term physiological signals (heart rate, EDA, respiration, skin temperature) are known to be modulated by posture, movement, thermoregulation, and autonomic state; in mobile field settings, these factors can dilute linear associations with pollutants even when exposures are accurately measured. In this multiplicity, patterns of correlation-strength and model-based cheques align with a literature that has demonstrated strong requirements on rigorous garment-sensor design and strong textile integration as conditions to extract meaningful behaviour-conscious environmental physiology correlations. Similarly, electrochemical modalities that use sweat (e.g., conductive-polymer sensors) can add information to inference by recording biochemical correlates of stress and hydration (Gualandi et al., 2021), and mechanical channels provided by strain-sensitive yarns can provide motion context to interpret cardiorespiratory signals (Ma et al., 2021).

Methodologically, the comparison of materials with the same session structure, location, activities and time correspondence offered a better understanding of how integration decisions carry over into field performance. The fact that CNT yarns and composite yarns retained more steady electrical characteristics over washing and activity is consistent with the scaled manufacturability of weavable, dyeable, robust yarns to use in high-throughput apparel processes (Zeng et al., 2021). On the other hand, the higher conductivity of AgNW networks still suggests them as high-fidelity channels where replacement or protective over-coatings are permissible (Zhu et al., 2020), and silver-printed electrodes can be used with biopotentials provided that washing conditions are well-regulated (Nigusse et al., 2020). Hybrid graphene/CNT e-textiles and rGO/PU coatings offer a desirable compromise, being sensitive, yet washable and breathable (Yao et al., 2021). Taken together, these pieces of evidence point to a portfolio approach where materials and integration strategies are chosen by garment area and sensing functionality instead of one best textile across all channels.

A number of constraints qualify conclusions. The research focused more on integration feasibility and operational characterization than on long-term clinical outcomes; therefore, the relationships provided in this study should be considered short-term relationships in naturalistic environments. The environmental variables were measured at wearable timescales

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but not necessarily with the analyte-specific selectivity of lab-grade gas sensors; future iterations should evaluate textile-integrated chemoresistive stacks targeted explicitly at NO_2 and related oxidants (Oluwasanya et al., 2022; Khan et al., 2024). Although washing analysis revealed significant degradation behaviour, standardised laundering procedures and failure analysis (e.g., microscopy of crack networks, adhesion testing) would help elucidate mechanisms in materials and coatings (Zhu et al., 2020). Lastly, the energy analysis was limited to device-level usage, which could be extended to thermoelectric or other energy-harvesting fabrics to allow continuous use in high-need conditions and should be considered in longitudinal deployments (Liu et al., 2023).

An architecture based on garments that expressly binds conductive materials, integration strategies and multi-domain sensing can provide actionable performance intelligence during everyday wear. AgNW systems are unrivalled in terms of peak conductivity but require protective measures to maintain functionality through laundering; CNT-based and composite yarns provide durable and scalable conduction and strain channels; graphene-family coatings and hybrids provide a compelling tradeoff between sensitivity and washability; and conductive-polymer chemistries provide biochemical sensing paths on the fabric surface (Olivieri et al., 2023). In the future, fabric-level selectivity to pollutants, light-responsive UV sensing, environmentally friendly inks, and self-powered functionality are all achievable and can be easily mapped on the design implications revealed by findings (Khan et al., 2024; Liu et al., 2023). Smart textiles have the potential to become a significant instrument in environmental-health monitoring at scale by integrating materials engineering with field-ready sensing and analytic discipline (Tang et al., 2022; Chowdhury et al., 2025).

5. Conclusion

This paper takes smart textiles out of benchtop potential and into field-ready practise by integrating conductive materials with coordinated environmental and physiological sensing in daily life. Comparative analysis showed that silver-nanowire networks have the best conductivity but the shortest wash life; CNT/composite yarns had repeatable and scalable channels with excellent wash life, and graphene- or PEDOT: PSS-based coats had breathability and sensing fidelity. Time-congruent analyses revealed plausible exposure distributions and high levels of co-variation among environmental factors, whereas environment physiology correlations were weak when activity and microclimate were factored. These trends highlight that garment design and integration strategy are not only about nominal conductivity, control signal stability, power budget and interpretability in the field. In practice, findings justify a portfolio strategy whereby materials and fabrication strategies are mapped to garment regions and sensing functions (e.g., high-fidelity leads vs motion or context channels). Methodologically, the pipeline session metadata standards, exposure categorization, correlation-strength visualization, and model checks provide a reproducible template for multi-domain wearable studies. Limitations include the absence of long-term clinical endpoints and analyte-selective fabric chemistries. Future work should integrate selective NO_2/oxidant layers, fabric-level UV dosimetry, standardized laundering failure analysis, and hybrid power strategies (duty cycling plus thermoelectric harvesting) to enable sustained, population-scale deployments. Taken together, the findings delineate actionable design rules for robust, energy-aware, and interpretable textile systems for environmental–health monitoring.

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